

**OFFICE OF NAVAL RESEARCH
END-OF-THE-YEAR REPORT
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS/STUDENTS REPORT**

for

CONTRACT: N00014-94-C-0088

PR Number 97-3134003ess-01

Bi₂Te₃/Sb₂Te₃ Superlattice Structures for High-ZT Thermoelectric Cooling Devices

Principal Investigator: Dr. Rama Venkatasubramanian

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Date Submitted: July 7, 1997

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Principal Investigator: Dr. Rama Venkatasubramanian

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a. Number of papers submitted to refereed journals, but not published: 1

b. + Number of papers published in refereed journals: 2

c. + Number of books or chapters submitted, but not yet published: _____

d. + Number of books or chapters published: _____

e. + Number of printed technical reports/non-refereed papers: _____

f. + Number of patents filed: 2*_____

g. + Number of patents granted: _____

h. + Number of invited presentations: 2_____

i. + Number of submitted presentations: 1_____

j. + Promotions: 1_____

k. Total number of Full-time equivalent Graduate Students and Post-Doctoral associates supported during this period, under this R&T Project Graduate Students: _____

Post-Doctoral Associates: _____

the number of

Minority* Graduate Students: _____

Minority* Post-Doctoral Associates: _____

and, the number of

Asian Graduate Students: _____

Asian Post-Doctoral Associates: _____

l. + Other funding (list agency, grant title, amount received this year, total amount, period of performance and a brief statement regarding the relationship of that research to your ONR grant): _____

*** One patent filed and one more to be filed**

a. Papers Submitted to Refereed Journals/Proceedings, not published

- 1) R. Venkatasubramanian and T.S. Colpitts "Enhancement in Figure-of-Merit with Superlattice Structures for Thin-Film Thermoelectric Devices", Proc. of the Materials Research Society Symposium on Thermoelectric Materials - New Directions and Approaches, To be Published in 1997.

b. Papers Published in Refereed Journals

- 1) R. Venkatasubramanian, T. Colpitts, E. Watko, M. Lamvik, and N. El-Masry, "MOCVD of Bi_2Te_3 , Sb_2Te_3 and their superlattice structures for thin-film thermoelectric applications", *J. Crystal Growth*, Vol 170, (1997) pp. 817-821.
- 2) R. Venkatasubramanian, "Thin-Film Superlattice and Quantum-Well Structures-A New Approach to High-Performance Thermoelectric Materials" *Naval Research Reviews*, Four/1996, Vol XLVIII, pp. 31-41.

f. Patents Filed

- 1) *Low-Temperature Chemical Vapor Deposition and Etching Apparatus and Method (Final Patent Filed Based on a temporary filing of USSN/60/016,701)*

An apparatus and method for the growth and etching of materials where a substrate on which a film is being deposited or which is being etched is maintained at a lower temperature than a precursor cracking temperature. This invention is critical to the growth of single-crystalline Bi_2Te_3 and Sb_2Te_3 materials and high-quality superlattice structures in these materials. Also, the apparatus embodied in this invention is of generic relevance to the deposition and etching of a variety of electronic and other materials.

- 2) *Ultra-low resistivity contacts to Bi_2Te_3 -related thermoelectric materials for high-performance thermoelectric devices (Invention Disclosure and Patent to be filed)*

This invention describes a method-using a combination of a special surface termination to a p-type $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ superlattice or similar materials and a specific metallization scheme-to achieve extremely low contact resistivities (in the range of $2\text{E}-8$ Ohm-cm²). This would be critical to the successful application of thin-film $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ superlattice structures in practical thermoelectric devices.

h. Invited Presentations

- 1) R. Venkatasubramanian, "Enhancement in Figure-of-Merit with Superlattice Structures for Thin-Film Thermoelectric Devices", 1997 Spring Meeting of Materials Research Society Symposium on Thermoelectric Materials - New Directions and Approaches, San Francisco, April 1997.
- 2) R. Venkatasubramanian, T.S. Colpitts, M. Lamvik, and N. El-Masry, "Growth and Characterization of Bi_2Te_3 , Sb_2Te_3 and their Superlattice Structures", 1997 Meeting of American Association of Crystal Growth (West), Stanford Sierra Campus, June 1997.

i. Submitted Presentations

- 1) R. Venkatasubramanian, E. Siivola, T. Colpitts, T. Volckmann and H.B. Lyon, "Comparative Properties of $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ Superlattice Structures and $\text{Bi}_{2-x}\text{Sb}_x\text{Te}_3$ Alloys", Presented at the American Physical Society Symposium on Novel Thermoelectric Materials I, Session F-27, Kansas City, March 1997.

j. Promotions

- 1) R. Venkatasubramanian, Promoted to Senior Research Engineer II and Leader for the Thermoelectrics Group, Center for Semiconductor Research, Research Triangle Institute.

a) Principal Investigator: Dr. Rama Venkatasubramanian

b) Current Telephone Number: (919)-541-6889

c) Cognizant ONR Scientific Officer : Dr. John Pazik

d) Description of Project: The goal of this project is to demonstrate factorial improvement in the thermoelectric figure-of-merit (ZT) with thin-film $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ superlattice (SL) structures compared to state-of-the-art bulk $\text{Bi}_{2-x}\text{Sb}_x\text{Te}_3$ alloys for high-performance thermoelectric devices. The motivation for the use of SL structures has been the hypothesis that the atomic size and mass differences at the SL interfaces as well as the periodic SL structure result in enhanced phonon scattering leading to a reduction in lattice thermal conductivity. The SL structures, consisting of pure Bi_2Te_3 and Sb_2Te_3 materials, are also expected to offer higher electrical conductivities compared to alloyed materials through reduced alloy-scattering of carriers and therefore larger carrier mobilities. With a successful demonstration of the enhancement in the thermoelectric properties of the $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ SL structures, another objective would be to address specific issues related to the development of a viable thin-film thermoelectric device technology.

e) Significant results during last year: Metallorganic chemical vapor deposition (MOCVD) has been shown to enable the growth of high-quality, thin-film, Bi_2Te_3 , Sb_2Te_3 and their SL structures. The 3ω method for the measurement of thermal conductivity of the thin-film SL structures and the $\text{Bi}_{2-x}\text{Sb}_x\text{Te}_3$ alloy films were established the previous year. *Our initial data on the thermal conductivity of short-period $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ SL structures, perpendicular to the SL interfaces, represented a first reported observation of a significant reduction (by a factor of five or more) in the thermal conductivity compared to those of solid-solution alloys [1].* During last year, we have observed thermal conductivity values as low as 1.3 to 1.4 mW/cm-K in a 30Å/30Å $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ SL; this is almost a factor of seven smaller than those of comparable BiSbTe_3 alloy thin-film. Similar low thermal conductivities have been observed in other optimized short-period SL structures. Measurement of the thermal conductivity values in a variety of $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ SL structures suggest that a distinction can be made where certain types of periodic structures may correspond to an ordered alloy rather than an SL, and therefore, do not offer a significant reduction in thermal conductivity. *Our study also indicates that $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ SL structures, with little or weak quantum-confinement, offer an improvement in the thermoelectric power factor over conventional alloys due to reduced alloy scattering in SL structures.* The power

factor and the electrical transport data in the plane of the SL interfaces have been used to provide preliminary support for this argument. The higher mobility at 300K and the temperature dependence of the mobility in SL structures between 300K and 77K are consistent with the experimental observation that the $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ SL structures offer higher Seebeck coefficients and thermoelectric power factor compared to typical commercial bulk alloys at cryogenic temperatures. These results offer evidence that the short-period SL structures potentially offer factorial improvements in the three-dimensional figure-of-merit (ZT_{3D}) compared to current state-of-the-art bulk alloys. During last year, we also developed low-resistivity contact metallization to p-type $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ SL structures to enable the direct measurement of electrical resistivities perpendicular to the SL interfaces. Using a specially-terminated surface to the p-type $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ SL and an optimized metallization scheme, we were able to obtain contact resistivities as low as $2.2\text{E-}8 \text{ Ohm}\cdot\text{cm}^2$ in transmission line model measurements. We believe, such low-contact resistivities would be invaluable for a thin-film proto-type device development.

f) Summary of Plans for Next Years' work: We plan to grow micron-thick p-type $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ SL structures and process them into small-area thermoelements to enable the measurement of the electrical resistivity and the Seebeck coefficient for the determination of the power factor perpendicular to the SL interfaces. This vertical power factor determination, in conjunction with the measurement of thermal conductivity perpendicular to the SL interfaces by the 3ω technique, can provide the figure-of-merit (ZT) directly.

g) Graduate Students and Post-Doctoral Associates working on the project:
None

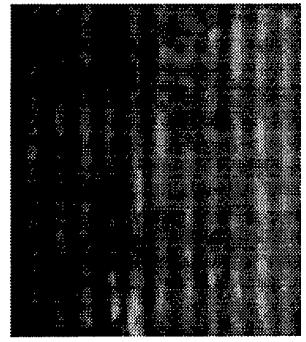
[1] R. Venkatasubramanian, T. Colpitts, E. Watko, and J. Hutchby, Proc. of 15th Inter. Conf. on Thermoelectrics (IEEE, Piscataway, NJ, 1996), Catalog No. 96TH8169, pp. 454-458

$\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ SUPERLATTICE STRUCTURES FOR HIGH-ZT THERMOELECTRIC COOLING DEVICES

R. Venkatasubramanian, Research Triangle Institute

OBJECTIVES:

- ◆ Demonstrate factorial improvement in figure-of-merit (ZT) with thin-film superlattice (SL) structures over state-of-the-art bulk materials
- ◆ Demonstrate thermal conductivity reduction in SL structures compared to bulk alloys due to additional phonon scattering mechanisms
- ◆ Demonstrate improved carrier mobility leading to higher electrical conductivity (σ) in SL structures, over bulk alloys, due to reduced alloy scattering of carriers
- ◆ Address critical issues in the development of thin-film thermoelectric cooling devices



24 nm

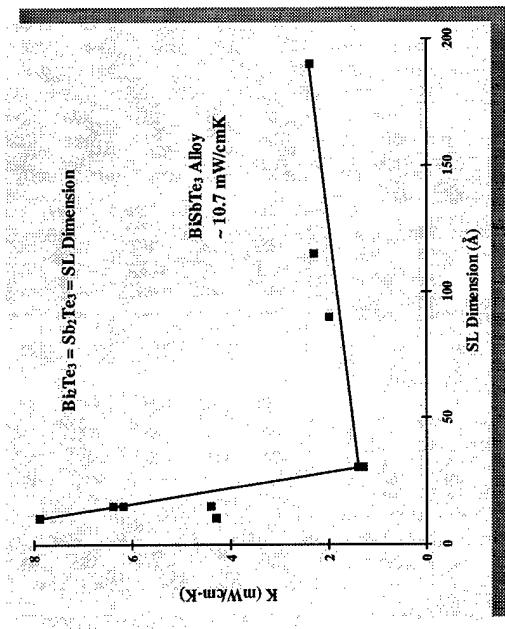
TEM view of $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ SL

APPROACH:

- ◆ MOCVD Growth of $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ SL structures
- ◆ Characterize thermoelectric properties including thermal conductivity by 3- ω method
- ◆ Address key issues in developing practical thin-film devices like low-resistivity Ohmic contacts to Bi_2Te_3 -related materials
- ◆ Demonstrated ultra-low resistivity contacts to Bi_2Te_3 -related materials by *surface engineering* of the $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ SL
- ◆ ACCOMPLISHMENTS:
 - ◆ Demonstrated good quality $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ SL structures based on TEM data (shown above) and X-ray diffraction
 - ◆ Experimental evidence for significant thermal conductivity reduction in $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ SL structures
 - ◆ Experimental evidence for higher Seebeck coefficient leading to improved power factor at 300K and cryogenic temperatures
 - ◆ Potential for ZT improvement by a factor of 3 compared to state-of-the-art bulk alloys
- ◆ TRANSITIONS & IMPACT:
 - ◆ Teaming with Marlow Industries on experimental evidence for advantages of $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ SL films for cryogenic cooling
 - ◆ Potential ZT enhancement offered by SL thin films can have a major impact on cooling of ship-board and other electronics; cooling for superconducting and IR-devices operating near 77K

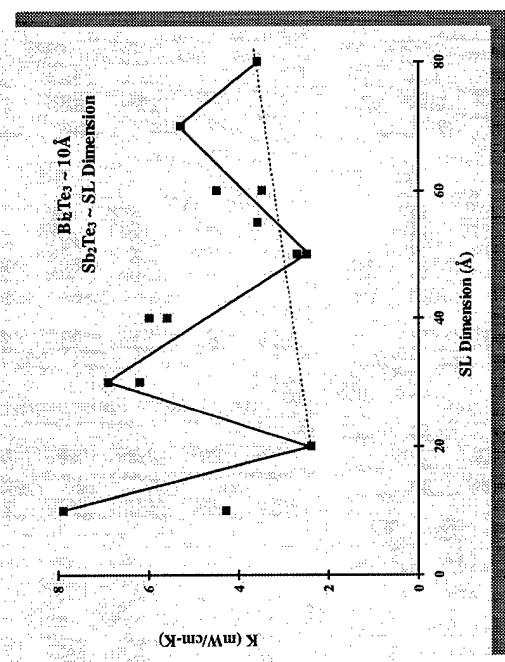
THERMAL CONDUCTIVITY REDUCTION IN SYMMETRICAL AND NON-SYMMETRICAL $\text{Bi}_2\text{Te}_3/\text{Sb}_2\text{Te}_3$ SL

Symmetrical SL



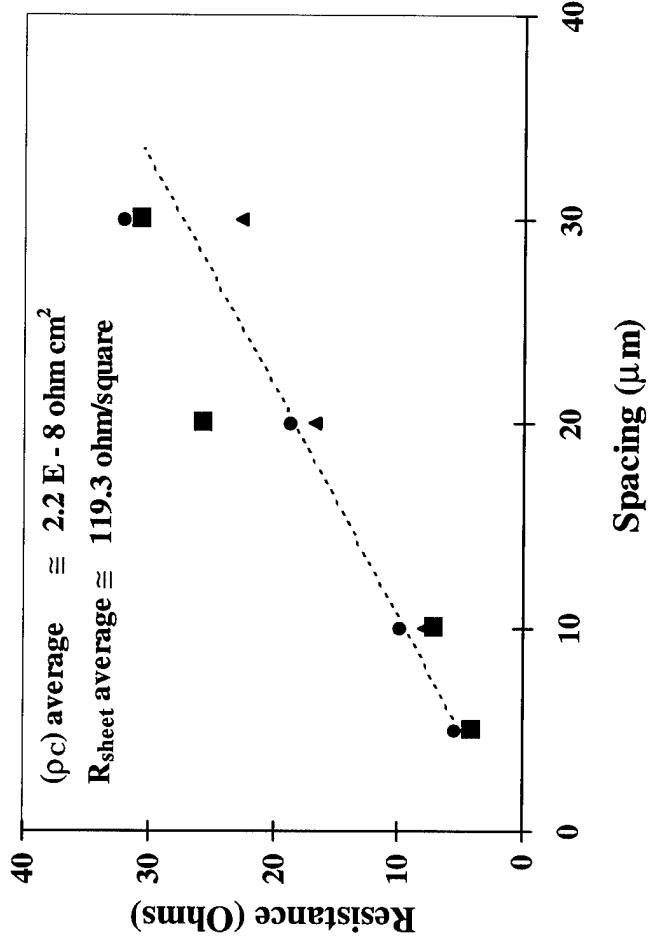
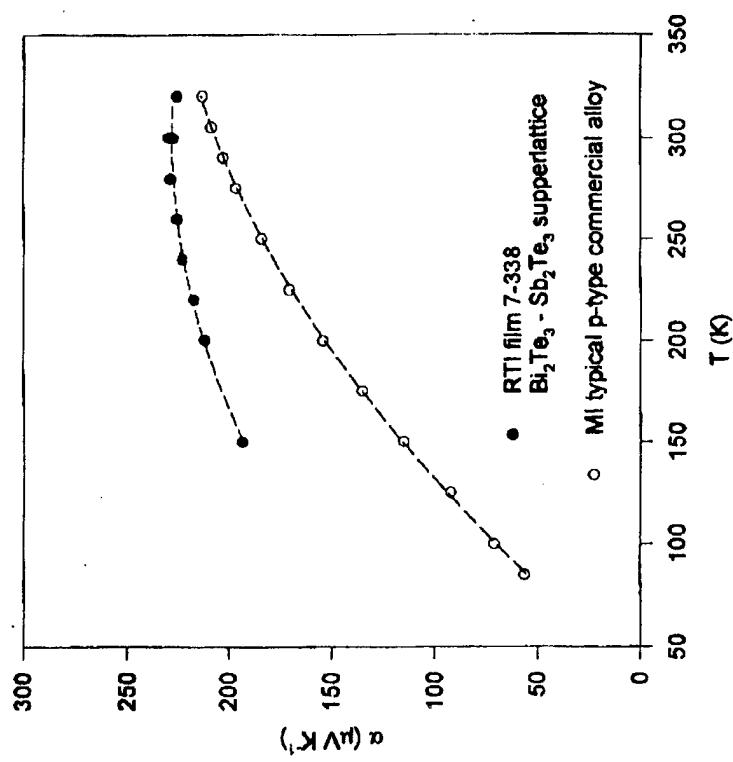
- ◆ Observed thermal conductivity of 1.3 to 1.4 mW/cm-K for 30Å/30Å SL
 - ◆ Factor of 7 reduction in thermal conductivity at 300K

Non-Symmetrical SL



- ◆ Apparent minima in K when thickness of Bi_2Te_3 plus Sb_2Te_3 layers are multiples of unit cell size $\sim 30 \text{ \AA}$, $\sim 60 \text{ \AA}$, $\sim 90 \text{ \AA}$
 - ◆ Compared to BiSbTe_3 and $\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3$ alloys over factor *perpendicular to SL interfaces* are

OTHER KEY RESULTS WITH Bi₂Te₃/Sb₂Te₃ SL STRUCTURES



- ◆ Bi₂Te₃/Sb₂Te₃ p-type SL structures offer higher Seebeck coefficients and power factor compared to typical commercial bulk alloys at 300K and cryogenic temperatures
- ◆ Bi₂Te₃/Sb₂Te₃ SL structures, with little or weak quantum-confinement, offer an improvement in the thermoelectric power factor over conventional alloys due to reduced alloy scattering
- ◆ Transmission line model (TLM) measurement to obtain contact resistivity
- ◆ A specially terminated surface to the p-type Bi₂Te₃/Sb₂Te₃ SL-surface engineering- and an optimized metallization scheme to achieve contact resistivities ~2.2 E-8 ohm-cm²
- ◆ Significant for a prototype thin-film device development with SL structures